TECHNOLOGY AND MARKET CHALLENGES TO MAINSTREAM THIN-FILM PHOTOVOLTAIC MODULES AND APPLICATIONS

Rajeewa R. Arya
Arya International, Inc.
P.O. Box 6852,
Williamsburg, VA 23188, USA
E-Mail: rajiv@arya-international.com

ABSTRACT: Technology and manufacturing advances over the past 25 years has led to widespread commercial use of thin film modules in many consumer applications. The three leading thin film solar module technologies are - amorphous silicon alloys (a-Si), copper indium diselenide alloys (CIGS), and cadmium telluride CdTe). These three technologies have demonstrated solar cells with efficiencies ~13% (a-Si), ~19% (CIGS), and ~16.5% (CdTe) respectively. Large area power modules are in various stages of initial production with these technologies and the module performance is in the 6%-11% range. Several manufacturing plants are in operation with plant capacities ranging from 3 MW to 30 MW. These plants are continuously increasing production with the present annual production of 1 MW to 5 MW. Technical challenges lie ahead in improving the module performance by reducing the gap between R&D cells and manufactured products so that they can successfully compete with crystalline silicon modules. Reliability of thin film modules in systems has been demonstrated with all three technologies with a fair degree of success. Several 1-480 kW grid-connected thin film module arrays are in deployment worldwide. Thin film modules are finding increasing acceptance for BIPV applications like roofs, facades, awnings etc. used in residential and commercial buildings. The cost of modules and market acceptance with new technologies still remains a major challenge to successful penetration of mainstream photovoltaic markets.

Keywords: a-Si, CdTe, $Cu(InGa)Se_2$, PV Module, Thin Film

1 INTRODUCTION

Thin-film solar cells and modules have been of scientific, technological, and commercial interest for over 25 years because they have held the best hope for low cost photovoltaic power generation. Three thin-film photovoltaic technologies have emerged as contenders for large scale applications. These are based upon (i) Amorphous-Silicon and its alloys, (ii) Copper-Indium Di-selenide and its alloys, and (iii) Cadmium Telluride. Research on thin-film solar cells with these materials started in earnest in the early seventies and it continues to be a vibrant endevour. The first commercial product (calculator modules) with thin-film solar cells entered the marketplace in early eighties. In the past two decades the technologies have made large strides in research, development, and manufacturing – today there are a whole gamut of products, from small calculator modules to large-area power modules which address consumer, architectural, and the BIPV power generation market segments.

2 BASIC THIN FILM MODULES

Thin Film modules for the three leading technologies have been developed with two basic configurations in the device structure: (1) *superstrate configuration* using glass as the superstrate, and (2) *substrate configuration* using stainless steel or Plastic foil/ribbon [1]. In these two configurations light enters the solar cell device either through glass or through a transparent plastic like Tefzel. The *superstrate* and the *substrate* configurations are schematically depicted in Figure 1 and Figure 2 respectively.

For Amorphous Silicon and its alloys both configurations employ optical enhancement to maximize absorption of incoming light. This is accomplished by light-scattering (either from front contact or from back contact) and reflection from the rear contact. While both configurations have a front contact which is a transparent conducting oxide (TCO) like tin oxide, indium-tin-oxide, or zinc oxide, in *superstrate configuration* the TCO is relatively thick (~600 nm) and textured while in *substrate configuration* the front contact is thin (~20 nm) and coats the textured substrate. The semiconductor thin-films layers within the two contacts can be a single junction p-i-n (a-Si), a tandem junction p-i-np-in, or a triple junction p-i-np-i-np-in. The tandem or triple junction configurations employ either all a-Si: H intrinsic layers or a combination of a-Si: H layers and a-SiGe: H alloy layers and/or microcrystalline silicon layers.

For Cadmium Telluride technology only the superstrate configuration is employed and a single junction. The device structure generally used is:

Light => glass/TCO/CdS/CdTe/back contact

with light entering from the glass side.

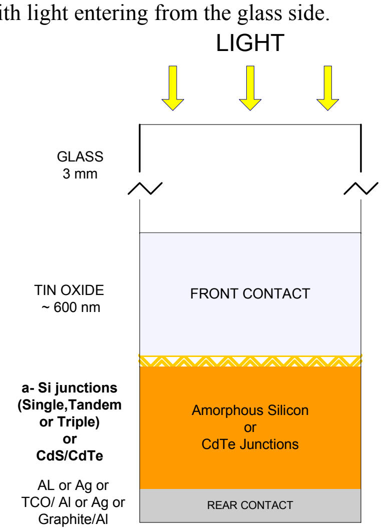

Figure 1: Superstrate configuration of thin film solar cells.

For Copper-Indium-diselenide and its alloys only the substrate configuration is employed. The front and rear contacts are generally ZnO and Mo thin films respectively and the device structure generally used is :

glass or Foil /Mo//CIGS/CdS/ ZnO <= Light

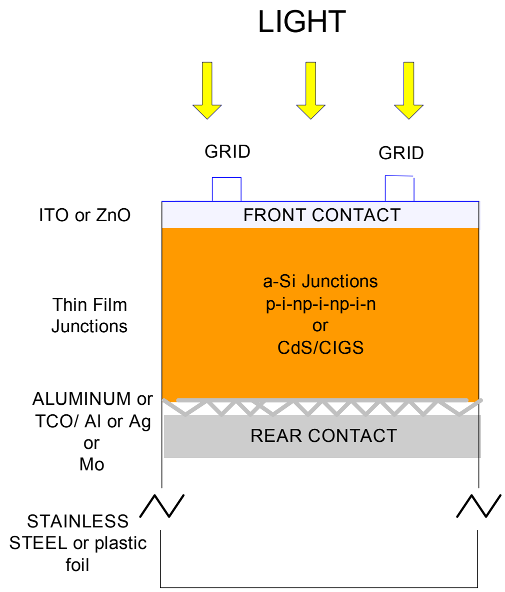

Figure 2: Substrate configuration of thin film solar cells.

with light entering from the ZnO side. For Flexible modules the glass substrate is replaced by either Mo foil or Mo coated plastic foil/ribbon.

The above configurations and device structures are completed into solar panels by two methods. First, for rigid substrates like glass, solar cells are integrated into panels by using laser/ mechanical scribing as shown in Figure 3.

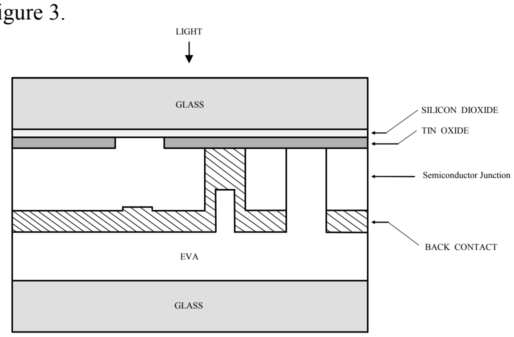

Figure 3: Laser / Mechanical scribe interconnect scheme with glass/EVA/glass laminate.

Second, in the flexible substrate configuration the foil/ribbon is cut into slabs of solar cells and are tabbed and interconnected in a manner similar to that done for crystalline solar cells. An example of the semi-automatic module assembly used by United Solar Ovonics Corporation for their a-Si technology is shown in Figure 4 [2].

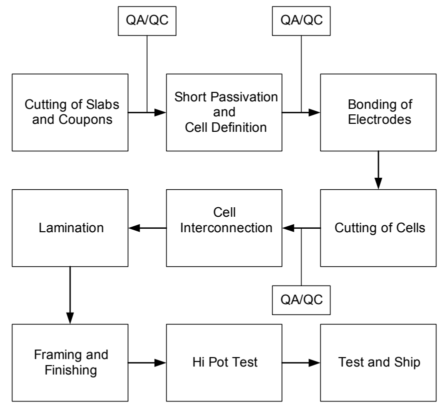

Figure 4: Semi-automatic module assembly operation for amorphous silicon modules on flexible substrates.

3. STATUS OF SOLAR CELLS AND MODULES

3.1 Solar Cells

The historical development of the “best in laboratory” thin-film solar cells is shown in Figure 5. Some “best” results with these technologies are shown in Table 1.

Table 1: PV parameters of some highest efficiency thin film cells

Organization	Technology	Efficiency (%)
UniSolar	a-Si /a-SiGe/a-SiGe	13.0
UniSolar	a-Si/a-SiGe/µx Si	13.0
Kaneka	a-Si/µx Si	12.0
IP, Julich	a-Si/µx Si	11.2
NREL	CIGS	19.3
ÅSC-UU	CIGS	16.6
NREL	CdTe	16.5

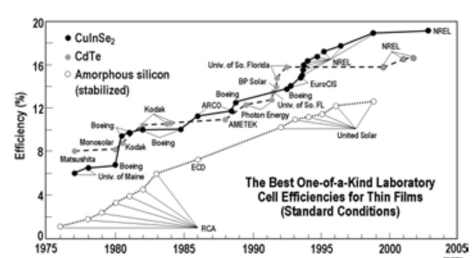

Figure 5: Historical Development of “best one-of-a-kind” laboratory thin-film solar cells [3].

3.2 Modules

All three technologies have been scaled-up and integrated into large area modules for mainstream photovoltaic applications. The major industrial producers for thin film modules are: (i) United Solar Ovonic Corporation (previously known as Uni-Solar), Kaneka, Energy Photovoltaics, Mitsubishi Heavy Industries, and RWE Schott Solar for amorphous silicon based technology, (ii) Energy Photovoltaics, Honda Engineering, Global Solar Energy, Shell Solar Industries (SSI), Showa Solar, and Wurth Solar for CIGS based technology, (iii) First Solar for cadmium telluride based technology.

The status of the "champion" large area module from different organizations with the three leading technologies is shown in Table 2 [3,6].

Table 2: Champion thin-film module performance

Company	Size (cm^2)	Efficiency	Power (W)	Date
a-Si & µ Si				
Kaneka	3738	10% *(estimated)	38 (est)	9/00
Kaneka	3825	12.48**	47.7	02/03
United Solar	4519	7.9% *	35.7	6/97
MHI	2000	11.2**		
United Solar	9276	7.6% *	70.8	9/97
BP Solar	7417	7.6% *	56	9/96
EPV	7432	5.7% *	42.3	10/02
CIS and alloys				
Shell Solar	3626	12.8%	46.5	3/03
Showa Shell+	3459	13.4%	46.45	8/02
Global Solar	7714	7.3%	56.8	3/02
Wurth Solar	5932	12.5%	74	5/02
CdTe				
BP Solar	8390	11.0%	92.5	9/01
First Solar	6612	10.1%	67.1	12/01
Matsushita	5413	11%	59	6/00
Antec Solar	6633	7%	46.7	11/01

+ 4 one ft modules laminated together
* stabilized
** initial

3.3 Commercial Production

Commercial production of thin film modules is still in its early stages . Amoung the three thin films, amorphous silicon has the most mature manufactruing technology but CIGS manufacturing is catching-up fast. While Table 2 and Figure 5 summerise the status of research, development and scale-up of the thin film technologies for power applications, where are these technologies in commercial production? Many of the organizations mentioned above have pilot production or production plants with capacities in the 10 MW to 30 MW range while the actual production is in the 1 MW to 5 MW range. Most of them are scaling-up their initial pilot production. Several organizations make a host of products starting from consumer applications (5 W to 20W) upto 100 W products for mainstream power applications. While the performance in terms of W/m^2 of thin film products is lower than commercially availble crystalline and polycrystalline products they are competively priced even though they are produced at much lower volumes. Table 3 summerizes the performance of some commercial products measured at NREL for crystalline and polycrystalline silicon modules as well as some thin film modules. The temperature co-efficient is complied from the manufacturer's spec-sheet [6].

Table 3: Performance of commercial modules measured at NREL

Organi-sation	Product	Technology	η (%)	T_{coeff} (%/C)
Sanyo	HIP190BA2	HIT	16.1	-0.33
Sharp	NT-185-U1	Single Si	14.2	
BP Solar	BP4170	Saturn	13.5	-0.5
Kyocera	KC167G	Cast Multi	13.1	
RWE	ASE300DGF	EFG Ribbon	13.0	-0.47
Sharp	ND-167-U1	Multi-Si	12.8	
BP Solar	BP360	Multi-Si	12.7	-0.5
ShellSolar	SQ 160-C	Single Si	12.1	-0.52
Evergreen	EC115	String Rib.	11.6	-0.4
GE	GEPV-165M	Single Si	11.5	-0.5
Shell	S115C	Multi Si	11.1	-0.45
WurthSolar	WS31050/80	CIGS	11.0	-0.36
ShellSolar	ST-40	CIS	9.4	-0.6
FirstSolar	FS55	CdTe	7.6	-0.25
Kaneka	LSU	Single a-Si	6.9	
Uni-Solar	US-64	Triple a-Si	6.7	
MHI	MA 100	Single a-Si	6.4	-0.2

It is expected that the total U.S thin film module production will exceed 50 MW by 2005. Table 4 summerizes some thin film products in the marketplace for power applications.

Table 4: Some thin film modules in the marketplace.

Organization	Technology	Power Rating
UniSolar	a-Si alloys	68 W
MHI	a-Si alloys	100 W
Kaneka	a-Si alloys	58 W
EPV	a-Si alloys	40 W
Shell Solar	CIGS	40 W
Wurth Solar	CIGS	80 W
Global Solar	CIGS	73 W
First Solar	CdTe	55 W

4. TECHNICAL CHALLENGES

Thin film technologies are still in their youth and offer a host of technical challenges and opportunities. The two major technical challenges are (i) performance improvemnts in terms of W/m^2 and (ii) Long-term reliability.

4.1 Performance Gaps

There exists a significant gap between the performance of commercial thin film products and the highest conversion efficiency demonstrated in the laboratory. While some of the difference is associated with "integration of cells to modules" losses, a major fraction of the gap is in the material and device quality when the thin film processes are scaled-up. For example, in amorphous silicon technology, Unisolar has demonstrated small area cell efficiency of ~13% [4]and 920 cm^2 module of efficiency ~ 10.5% [5] using production materials. Presently, their champion large area commercial module has an efficiency of ~7.6% and their 68 W product has and efficiency of ~ 6.7% [6]. This shows the opportunity for performance improvements that can be expected in time with the present technology. A similar situation exists for the CIGS and the CdTe technologies. In CIGS technology over ~19% efficient small area cells have been demonstrated [7] but the large area modules are in the 9%-11% range. In CdTe technology ~16.5% efficiency on small area solar cells has been demonstrated [8] but the best large area module from production still has an efficiency of ~7.6%. As the manufacturing processes mature, thin film modules have a good potential to compete in STC performance with the average crystalline silicon modules while holding an edge in performance in warm climates due to a lower temperature co-efficient of power loss with temperature as tabulated in Table 3.

4.2 Reliability

The long term stability and reliability of thin film modules has been a subject of much study since the mid-eighties. Early on light-induced degradation of amorphous silicon material and devices was studied and many material and device improvements have occurred in the past two decades. Two main features have greatly improved the light-induced instability – (i) thickness of the intrinsic layer [9] and (ii) the use of hydrogen dilution of silane in the gas mixture during the deposition of the intrinsic layer [10,11]. The light-induced-degradation has been "empirically engineered" by the use of multi-bandgap, multi-junction devices which use thin i-layers deposited with varying degrees of hydrogen dilution of the silane and other bandgap modifying gases. The degradation of single junction a-Si: H devices (~3000 A) are ~ 25% and the degradation of multijunction devices is between 12%-18%. Figure 6 shows the degradation of a triple junction device from Uni-Solar which stabilizes at 88% of its initial efficiency [2].

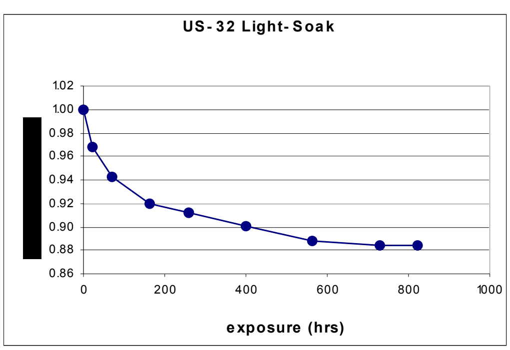

Figure 6: Long-term light-soaking of triple junction module under one sun illumination at 50 ^{0}C

Amorphous silicon panels have functioned well in outdoor testing and applications. Long-term outdoor reliability is a function of the "back-end" processes, such as, tabbing, lamination, wiring and junction termination. These "back-end processes" are different for the two technology configurations. In the *superstrate configuration*, generally, the solar cells are interconnected to form the module by monolithic laser or mechanical scribing during various stages of the solar panel production as shown in Figure 3. The solar panel is then laminated with EVA (Ethyl Vinyl Acetate) or a similar material and another piece of glass or TAP (Tedlar Aluminum Polymer). In the *substrate configuration*, the solar cells slabs are tabbed and laminated with EVA and Tefzel or glass. In both configurations, junction boxes and frames can be added.

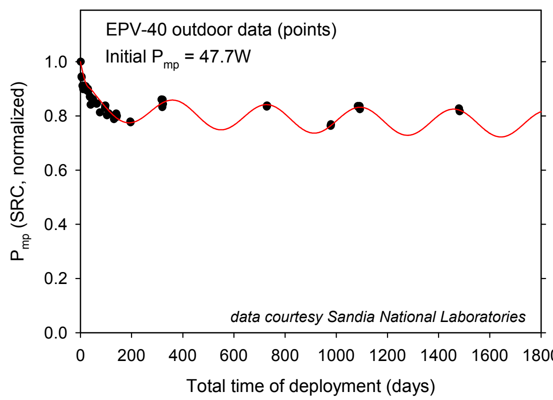

Figure 7: Long-term outdoor performance of a-Si/a-Si tandem junction module (EPV).

The outdoor reliability of modules is largely a function of the efficacy of the encapsulation and the packaging system in keeping moisture out of the active solar cells. Moisture ingression, contact reliability under thermal cycling and humidity-freeze cycling are the main modes of failure. Many organizations have developed packaging schemes that pass the testing requirements for 20 year outdoor applications. Figures 7 and 8 show the outdoor reliability of amorphous silicon based modules. In Figure 7 the module is an a-Si/a-Si tandem junction produced by EPV and studied at Sandia Laboratories [12]. In Figure 8 the performance of a 1 KW_p array of a-Si/a-SiGe modules produced by BP Solar and studied at NREL over a 10 month period is depicted. It is noteworthy to see that the array produced the rated power even at temperatures above 60 ^{0} C [13].

5. MARKETING CHALLENGES

5.1 Module Cost

The material costs in thin film modules are dominated by the "back end" costs of converting a solar panel into a module as in the *superstrate configuration* or solar cells into module as in *substrate configuration* on flexible substrates. The cost of thin film materials (gases, contacts, elements, compounds, TCO etc.) are a small fraction of the total material costs of the modules. The material costs distribution for framed and unframed amorphous silicon based modules is shown in Figures 9 and 10 respectively. While the example shown here is with amorphous silicon the picture is not significantly different with CIGS or CdTe technologies.

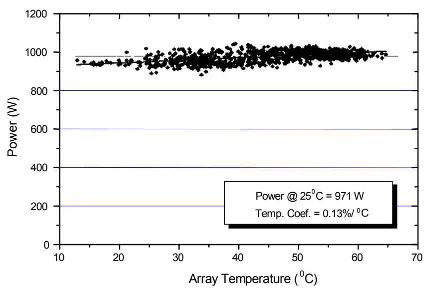

Figure 8: The output power vs. array temperature for a One kW_P array of 4 ft^2 BP Solar a-Si/a-SiGe tandem modules at NREL in Golden, Colorado.

In all three technologies the "advantage" of using "less material" in thin-film modules is largely offset by the use of conventional crystalline silicon "back-end" schemes of lamination and module termination.

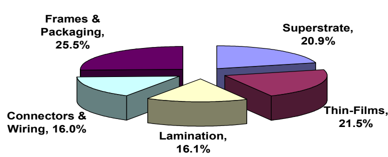

Figure 9: Material cost distribution for amorphous silicon based framed modules.

Development of frameless module mounting schemes and PV laminates on membranes are some encouraging approaches being pursued for amorphous silicon technology. For CIGS technology to some extent but certainly for CdTe technology edge sealing of the laminate is essential. The present solution of an edge sealant in a frame works adequately but adds costs to the module. This is an area in which development of thin-film encapsulants which can be applied as a viscous spray or a roll-on laminate can significantly reduce the overall costs of thin film modules.

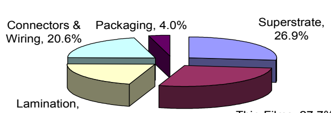

Figure 10: Material cost distribution for amorphous silicon based unframed modules.

5.2 Markets and Applications

Large area thin film modules are new in the marketplace and acceptance requires not only a significant cost advantage but also education of the many salient features of thin films which make them more appropriate for certain applications.

The unique attributes of thin film modules – automation and semi-automation in manufacturing, high manufacturing yields, flexibility in size and voltage outputs, aesthetic appearance and better performance at higher temperature than crystalline silicon all lead to making them a better product for building integrated photovoltaic applications (BIPV). Two examples of thin film modules for building application are shown below. In the first example a roll-on solar product offers much ease in roof installation.

Figure 11: PV laminates on membrane on metal roofs.

Figure 11 shows flexible a-Si laminates on membrane (Uni-Solar) on metal roof. a- Si – the ease of installation is remarkable [2]. Figure 12 shows a building façade in North Wales which generates 85 kW from CIS based thin film panels [14]. The aesthetics of both these applications show the distinct advantage thin film modules offer in BIPV applications.

Figure 11: 85 kW CIGS thin-film (Shell Solar) based BIPV façade installed at North Wales, UK

6. SUMMARY

In sum, thin film modules have come a long way in the past two decades. Several organizations are producing amorphous silicon alloy and copper-indium-gallium-selenide modules for various applications ranging from battery charging applications for cycles, cars, small appliances like TV, VCR and stereos in RV's, boats and remote cabins. Large area CdTe modules are being produced by one organization for power applications and is undergoing extensive field testing [14]. The present production volume of power modules is modest compared to the crystalline silicon modules but the products are slowly finding acceptance in niche BIPV applications like roofs, facades, awnings etc. used in residential and commercial buildings. To become a significant alternative to crystalline silicon modules, in mainstream photovoltaic applications, thin film modules still requires further improvements in module performance, costs and reliability.

7. ACKNOWLEDGEMENTS

The author would like to thank many colleagues in the thin-film PV community for their constant support and encouragement and for supplying information from their organizations in a timely manner.

8. REFERENCES

[1] R. R. Arya, MRS Spring Meeting, San Francisco, (2004), in press.

[2] S. Guha, Proc. of WCPEC-3, May (2003), in press

[3] K. Zweibel, Compiled for NREL, Revised March (2003).

[4] J. Yang, A. Banerjee, and S. Guha, Appl. Phys. Lett. 70, 2975 (1997)

[5] B. Yan, G. Yue, J. Yang, K. Lord, A. Banerjee, and S. Guha, Proc. Of WCPEC-3, May (2003), in press.

[6] B. Von Roedern, NREL, private communication.

[7] K. Ramanathan, M. J. Romero, C.S. Jiang, and R. Noufi, Proceedings of the European Materials Research Society 2004 Spring Meeting, Strasbourg, France, in press.

[8] X. Wu, R. Ribelin, R.G. Dhere, D.S. Albin, T. A. Gassert, S. Asher, D.H. Levi, R. Matson, H. R. Moutinho, and P. Shelden, Proceedings of the 28th IEEE Photovoltaic Specialists Conference, Anchorage, Alska, (200) 418

[9] M. Bennett, J. Newton and K. Rajan, Proc. of 7th European Photovoltaic conf., Seville, Spain, 544 (1986).

[10] S. Guha, K. L. Narasimhan, and S. M. Pietruszko, J. Appl. Phys., **52**, 859 (1981).

[11] M. Bennett, K. Rajan and K. Kritikson, Proc. of the 23rd IEEE Photovoltaic specialist Conf., 845 (1993).

[12] A. E. Delahoy, Y-M. Li, J. A. Anna Selvan, L. Chen, T. Varvar, H. Volltrauer, Proc. "PV in Europe" Conference, Rome, October (2002).

[13] R. R. Arya, Proc. of 11th International Workshop on the Physics of Semiconductor Devices, Delhi, India (2001).

[14] Harin Ullal, Proceedings 19th European Photovoltaic Solar Energy Conference and Exhibition, France, 2004, in press.